

# Prospective system analysis of stationary battery systems under the frame of Constructive Technology Assessment <sup>1</sup>

**Manuel Baumann** ([manuel.baumann@kit.edu](mailto:manuel.baumann@kit.edu)), Institute for Technology Assessment and Systems Analysis, Karlsruhe Institute of Technology

## Abstract

The ongoing German energy transition causes a higher demand for reliable energy storage in the future. This increasing demand for sustainable, cheap, safe and efficient energy storage systems has caused a stronger public debate about the potential benefits of grid battery storage according to sustainability. This circumstance led to the preposition that there is a need for the development of a proper ex-ante assessment strategy to support technology uptake. The developed approach represents a framework for prospective system analysis (PSA) using the heuristics of constructive technology assessment to identify consequences, application possibilities or threats in the technological trajectory of grid battery storage. Within this framework PSA is used to quantitatively assess economic, environmental and social aspects along the entire life cycle of electrochemical energy storage technologies in order to identify hotspots according to sustainability. The Analytic Hierarchic Process (AHP) supports multiple methods in data collection and enables the analyst to combine results from PSA with qualitative actor notions about technology according to the "world" where it is embodied. In this sense AHP enables to achieve an optimum construct of technology from a stakeholder view point. The developed approach represents an efficient research strategy to shape technology in a sustainable way in frame of „Responsible Research and Innovation“.

**Key-words:** Grid battery storage, energy turn over, electric energy time shift, socio-technical system, constructive technology assessment, Li-Ion, vehicle to grid, lead acid, life cycle costing

**JEL codes:** O0: General

---

<sup>1</sup> Based on the report for the unit "Project IV" of the PhD programme on Technology Assessment under the supervision of Dr.-Ing. Marcel Weil and Prof. Dr. António Brandão Moniz. The report was presented and discussed at the Doctorate Conference on Technology Assessment in July 2013 at the University Nova Lisboa, Caparica campus.

## **Introduction**

It is common sense that the German “Energiewende” represents a large socio-technical energy system transition which is characterized by increasing fluctuating renewable energy system (RES) capacities leading to a higher demand of energy storage technologies in the mid to long term (Armin Grunwald 2011, Genoese 2013, Wietschel et al., n.d., Leonhard et al. 2008). Battery storage systems with various existing as well as emerging chemistries and vertical system integration possibilities are such a storage technology in the foci of this research. They represent an enabling technology which improves the remaining electricity system, consistent of RES, grid infrastructure, residential power generation, power plants and regulation. Vice versa they are dependent on other energy system developments as well dynamics and do not represent a separately identifiable dominant system (Grünwald et al. 2012). Their success is dependent on hardly predictable future technical advances, actor preferences, development of competing technologies and designs, diverging interests of actors, future cost efficiencies and environmental performance as well as the evolution of market demand and design. All this dependencies can lead to engineering skepticism regarding technologic and economic viability or public concerns whether high costs of this technology might not outweigh possible benefits according to sustainability (Kemp 1994) within the energy system.

These conditions have inspired the current research leading to the preposition that there is a strong need to prospectively identify, exploit and exhaust possibilities to shape or select technology alternatives according to sustainability principles in a participative way (Grunwald 2012). Prospectively means in detail to avoid unintended effects as wrong investments, possible social conflicts, and negative environmental impacts over the entire life time of a new technology rather than to tackle them when they become apparent after technology has already penetrated society (Roes and Patel 2011). This results in the need of ex-ante assessment strategies which allow the identification and especially prioritization of such sustainability hotspots and provide a broader basis for decision making, early warning, actor modulation and finally technology support as well as selection. A major implication resulting from this task is the necessity to deal with two worlds, the external world of economics, chemistry, markets and the internal world of psychology, values, thought and of course decision making itself (Saaty and Begicevic 2010).

The kernel of this article is to establish a theoretical grounding to develop a research design satisfying this objective. In general the establishment of a proper research design represents the logical sequence connecting empirical data to research questions and most significantly to its conclusions (Perera

and Sutrisna 2010). Based on this supposition a brief overview of the ex-ante heuristic of constructive technology assessment (CTA) (Schot and Rip 1997) as a guiding principle of prospective system analysis (PSA) (Weil 2012) is given followed by a discussion of the latter. After this discussion the paper shifts to the design research methodology including a short discussion of the integral role of the Analytic Hierarchy Process (AHP) (T. L. Saaty 1990).

## Basic assumptions for the approach

In general, technology is part of a seamless web of highly related heterogenic elements as organizations (manufacturers, research and development, end users etc.) resources, scientific elements and legislation (law). The combination of these elements allows the achievement of functionalities of technology. Societal functions such as transport and energy supply are results of such clusters of heterogenic elements which can be named socio-technical systems (Geels 2005). Sustainability of mankind's development is highly dependent on such complex socio-technical systems which determine the demand for raw material and energy, needs for transport and infrastructure, emissions, mass flows of materials and composition of waste (Fleischer and Grunwald 2008), (Ravetz 1999).

The properties of new technology entering in such a system are not given beforehand, but they co-evolve with interactions which occur during development, implementation, adoption and wider use (Schot and Rip 1997). This is referred as "*co-evolutionary process*" and begins with an innovative product against an existing societal-technical regime which sets up the rules.

In the case of a bigger technological transition a replacement or reconfiguration of embedded socio-technical practices and regimes might occur and offer opportunities for new technologies (by creating new standards or dominant designs, changing regulations, infrastructure and user patterns (Grünwald et al. 2012)). But when a new (potentially sustainable) technology development occurs also irreversibility's can arise which are reinforced when actors start to invest in paths that seem to emerge (Rip and Kulve 2008, van Merkerk and van Lente 2005). Such irreversibility's can emerge e.g. through collective roadmaps representing articulated expectations which paths a collective of companies or an entire industry should follow (van Merkerk and

van Lente 2005). This can lead to continued re-investment in dominant designs, technology lock-in, sunk costs, economies of scale, technological interrelatedness or path dependency. This comes especially true for large socio-technical systems and might represent a major obstacle for swift towards a more sustainable energy system (Verbong and Geels 2010).

The shaping of a technology according to sustainability goals is thus dependent on the basic design parameters resulting from the heart of a temporally relevant technological regime, which also constitutes a framework of knowledge shared by the actors of this system (Kemp 1994). It is therefore crucial to understand existing regimes including dominant practices and landscape pressures to support the uptake of a new technology according to sustainability principles (Grünewald et al. 2012). To do so multi-actor dynamics should be taken into account in order to understand how innovation takes place in an existing or changing socio-technical system (van Merkerk and van Lente 2005).

## Principles of Constructive Technology Assessment

Constructive Technology Assessment (CTA) was developed in the Netherlands by (Schot and Rip 1997) and was adopted in several countries (Fleischer and Grunwald 2008). It is grounded in the theory of co-evolution of technology and society, emerging irreversibility and endogenous futures (Grunwald 1999). It has the aim to broaden and positively influence the technology development process by addressing potential innovation obstacles or impacts as early as possible (Hochgerner and et. al 2008), rather than assessing ex post the impacts of more or-less finalized products (Bell 2011). It represents a *"...soft intervention, attempting to modulate ongoing socio-technological developments, at least by making them more reflexive."* (Rip and Kulve 2008).

CTA includes non-technology development related actors which get in contact with the final product. These actors usually observe technologies from the outside and compare them with other parallel developments (so called comparative selectors). The specific technology only plays a small role for most of this kind of stakeholders (so called "black box effect"). Comparative indicators for technology selection as costs, applicability, environmental impacts and safety are more relevant for them (Hochgerner et. al 2008) (Rip

and Kulve 2008). In contrary developers are oftentimes not informed or not knowledgeable about development and issues at stake for different professional environments (e.g. business, end-use, government) (van Merkerk and Smits 2008) and are strongly technology focused. They are referred as "*Enactors*" which try to realize new technology and identify with it and tend to emphasize positive aspects (e.g. to think and work in "*enactment cycles*") as Rip and Kulve (2008) mentions.

CTA can serve as a bridging event making it possible to confront technology developers (*enactors*) with the visions, interests and expectations of users in a broader sense (*comparative selectors*). It can create and orchestrate spaces in which interaction can occur e.g. through workshops, interviews or surveys even if interactions between participants might be partial. Such interactions are mainly supported by socio-technical scenarios based on multilevel dynamics to show effects of interfering enactment and selection cycles and to give a solid base for the interactions (Rip and Kulve 2008).

However, the involvement and interaction between actors is claimed to grasp strategic intelligence from actors which enables the communication of (potential) broader implications of technology trajectory paths and emerging irreversibility's through endogenous futures. In this sense CTA offers a possibility to tackle the Collingridge dilemma which states that: in early technology development stages opportunities to steer are plentiful, but hard to choose from, while at later stages this is reversed (Kuhlmann 2013; Collingridge 1980)).

## Constructive technology assessment as a guiding heuristic for the research design

To sum up, CTA can be seen as an attempt to broaden the design of new technologies by a feedback of TA activities into the construction of technology. It has three major analytical achievements: socio-technical mapping, early and controlled experimentation enabling to identify unanticipated impacts and the creation of a dialogue between innovators, consumers and the public (Guston and Sarewitz 2002). CTA can include a manifold of alternative and creative methods or techniques for stakeholder modulation and involvement. However, CTA practitioners mostly use qualitative narrative methods expressed through prospective socio-technical scenarios, derived from stakeholders thoughts (Schreuer, Ornetzeder, and

Rohracher unknown, Rip and Kulve 2008, Douglas Keith Raymond Robinson 2010). In this way CTA participants can construct the meaning of a situation which is forged in discussions or interaction with each other and helps to understand the "world" in which participating individuals are embedded (Creswell 2003). Most CTA practitioners then try to interpret this meanings about the world and then somehow derives actions to support technology development. There are critics which state that this might reinforce the impression that such socio-technical scenarios and their interpretation might be very blurry and that their use is thus restricted to an exclusive forum (Kuhlmann 2013).

The presented research is not considered to be limited on the dominant narrative approaches within CTA. The focus of it is to prospectively identify and elicit values to exhaust possibilities to shape technology in a sustainable and participatory way. It requires a manifold of methods somewhere in a continuum between qualitative and quantitative to identify emerging problems related to technology development, which in their core represent complex decision problems embedded in an uncertain and hardly predictable environment. This makes it necessary to (Guston and Sarewitz 2002):

- build a continuously reflexive decision process to tackle uncertainty and unpredictability *"so that attributes of and relations between co-evolving components of the system become apparent, and informed incremental response is feasible"* (Guston and Sarewitz 2002).
- To prospectively analyze consequences of innovative technology leading to a better understanding and, if necessary, to modification of it.

This leads to the orientation of the work towards pragmatism also named as mixed methods (Creswell 2003). In this sense the research allows it to choose methods and procedures that meet the needs of the research on hand through the lens of CTA. This also includes the way of using data (e.g. qualitative and quantitative) through being not based on strict dualism between mind and a reality completely independent of the mind (Creswell 2003). The idea of CTA serves as a legitimating for the use of mixed methods within a pragmatic perspective (Creswell 2003, Murphy and Rorty 1990, Cherryholmes 1992). The methods used for this research are as mentioned before mainly grounded in the field of prospective system analysis or more specific in Life cycle thinking and multi criteria decision analysis.

## Prospective System Analysis

The need for system analysis emerged from the increasing complexity of modern technology. It is a collective term for mostly quantitative but also qualitative methods which are used for technology planning, development, broad assessment also from non-technical criteria (Grunwald 2002). Quantitative system analysis can help to reduce the complexity of a system and its surrounding by problem decomposition into sub-problems. The choice of the right system analysis tool depends on the specific research paradigm and question, technology as well of its development status. In case of the assessment of early development stage technologies the more distinct term "*prospective system analysis*" (PSA) is used (Weil 2012). Behind this term already somehow lies the guiding principle of CTA in using certain methods to look at drivers, effects or economic, social and environmental impacts of emerging technologies over their entire life cycle as early as possible in order to avoid unintended effects or at least rise attention to them and support technology design (Baumann 2013, Weil 2012).

Some typical quantitative and qualitative tools used for prospective system analysis tools are techno-economic assessments, economic-, social- and ecological life cycle assessment, material flow analyses, ABC-Analysis, energy system modeling and multi-criteria decision analysis methods (MCDA) etc. (Grunwald 2002, Grunwald 1999). Especially Life cycle based assessments as Life Cycle Assessment (LCA) and social Life Cycle Assessment (sLCA) are helpful methods to identify potential benefits and how sustainable a certain technology is in comparison to other alternatives. These approaches include the production, use phase as well as the disposal of products (cradle to grave). In this sense the use of LCA, LCC and sLCA can help to compare traditional product systems with a product that e.g. contains an innovative component. Comparing both products (traditional vs. innovative) makes it then possible to give a feedback to developers, manufacturers or decision makers about the specific impact of an innovative product system regarding different spheres expressed through numeric values (Weil 2012).

This work follows a combination of life cycle and techno-economic modeling based approaches including techniques as linear programming and probabilistic simulations. The combination makes it possible to enable a comprehensive quantitative evaluation of sustainability factors of the technical, environmental and economic performance of the technology in scope, to understand major system dynamics and to compare them to other technological options.

## Challenges of Prospective System Analysis regarding the research aim

Prospective system analyses methods as LCA and LCC are heavily dependent on data (e.g. quantitative inputs as energy, raw materials, ancillary, physical or required operation conditions, life time, maintenance, cost etc.) and are time consuming. Most assessments start with extrapolation of available data into the future by the development of scenarios (e.g. combination of learning curves, economies of scale, linear up-scaling with data from mature comparable systems etc.). Such scenarios have to be developed carefully and have to deal with high uncertainty of data and of their poor availability. At the same time prospective system analysis has to handle high complexity and tackle a high degree of freedom inherent in pre-market phases of a technology resulting in the before mentioned Collingridge dilemma. Complex system analyses as LCA, LCC of emerging technologies thus require assumptions (ad hoc suppositions), simplifications (e.g. ceteris paribus conditions) and sensitivity analyses based on somehow “physical” or more “tangible” factors – related to outside to some kind of objective reality (Saaty 1990).

This complexity and inherent uncertainty of early stage system analysis is reinforced by the unclear (or yet not existing) socio-technical embedment of an emerging technology. This situation makes it difficult to disaggregate or allocate technological, societal, environmental and economic impacts or benefits into a clear regime due to high complexity and dynamics of socio-technical systems. A prospective system analysis dilemma resulting from this is the uncertainty of the desirable technology “shape target” or weighting of results (environmental, economic impacts etc.) and how to present them to a certain peer group. This uncertainty is based on the fact that shape targets for an optimum technology construct are dependent on specific actors preferences which by contrast to physical / tangible factors represent a psychological realm claimed to be intangible as they are related to subjective ideas based on beliefs of the individual about himself or herself and the world of their experience (Saaty 1990).

As a result of this complexity and dependency on tangible factors and uncertainty a system analysts imagination might cause technology to proceed along a certain trajectory (in the way a rocket follows a trajectory as soon as it has been launched), based on a dominant socio-technical regime (market structures, technology etc.) serving as a base for modeling and result presentation. An example here fore might be notions about what the “market” (end users) wants and how new technology might be used (and



thus modeled within its use phase), but market demand does not articulate itself in a unambiguous and quantitative way (Kemp 1994). The articulation of extrapolations and "dynamics as usual" is problematic as markets evolve. At the end only a narrow view of sustainability of an emerging technology might be given caused by technological and economic realities and individual ideologies which are implicitly embedded in the modeling apparatus which results are claimed to be objective (Grunwald 2011).

## **Resulting implications for PSA**

The process of decision making represents an inherently forward looking activity, in which to a certain degree expectations about how the future will look like are dependent on any decision (Guston and Sarewitz 2002). The research builds up on the assumption that the way of shaping or selecting technology according to sustainability factors relies on the preferences and opinions from different actors embedded in different "worlds" resulting in a such a decision problem. This preferences or notions vary from one actor to the other as they are subjective, qualitative and impressionistic (Perera and Sutrisna 2010). These aspects make it challenging to determine which factors and methods should be integrated and applied when it comes to a decision problem.

In order to provide a solid base for technology support and decisions making through the heuristics of CTA it is not sufficient to use purely quantitative PSA tools to elicit judgments or to manipulate numbers to derive priorities of technology design or selection without having a clear understanding of why those factors were chosen and how they relate to the entire system development and its dynamics where decisions take place (Saaty and Begicevic 2010). This makes it necessary to e.g. conduct explorative interviews or a literature review in order to identify variables that influence the trajectory of technology within a complex socio-technical system. After doing so there is still the need to capture and put together all identified problems into reliable, reproducible structures associated with a multi-criteria and uncertain decision making environment.

Multi Criteria Decision Analysis models (MCDA) explicitly consider such complex decision problems and provide a possibility to tackle them (Goodwin 2004). Especially the Analytic Hierarchy Process (AHP) developed by (Saaty 1977) is such a method belonging to the field of MCDA which itself is a sub-

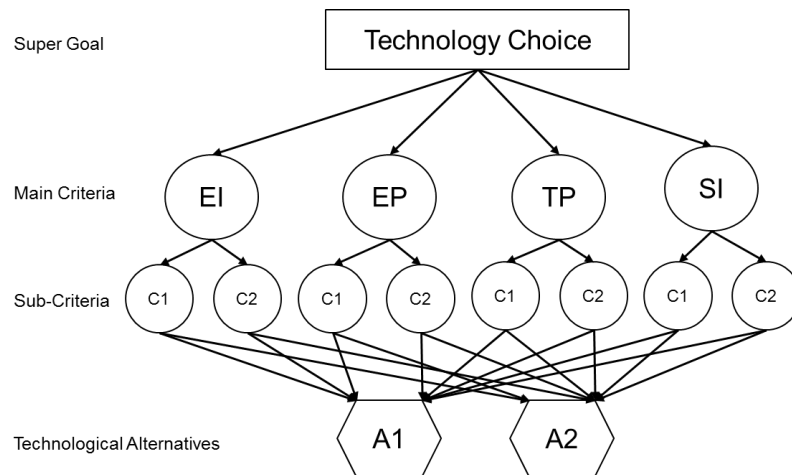
discipline of operation research. The method has already been widely applied to solve large scale socio-technical decision problems with intangible and tangible criteria according to energy policy planning as in the case of Finland (Hämäläinen and Seppäläinen 1986) or for the choice of the best renewable energy technology for sustainable energy planning (Demirtas 2013).

### ***Analytic Hierarchy Process (AHP) Principles***

In general AHP represents a non-linear framework for carrying out both deductive and inductive thinking, considering several factors simultaneously, allowing for tradeoffs to arrive at a synthesis (Saaty 1990). The method is based on mathematics and principles of psychology. It is a compensatory method which allows numerical trade-offs among various dimensions. As a 'normative' model it enables a decision maker to defend his choice over competing alternatives and to derive actions (e.g. to determine options/conduct priority for technology optimization) instead of describing the way a decision maker actually makes decisions through the use of descriptive models (Perera and Sutrisna 2010).

AHP requires the establishment of a hierarchic or a network structure representing the problem (Saaty 1987). Within this structure AHP refers to "attributes", "goals" and "alternatives". "Attributes" are considered as "objectives", "factors" or "criteria" e.g. economic performance and environmental impact. "Alternatives" is synonymous with technology "option", "policy" or "method" (Perera and Sutrisna 2010). At the top of this hierarchy is the "goal" or general objective of the decision process. Criteria related to the problem can be found below this goal. These criteria can be further decomposed into sub-criteria which also can be seen as constraints or refinements. Finally competing alternatives can be found at the bottom below the lowest-level criteria (Goodwin 2004).

Criteria can be identified through literature review or interviews with stakeholders. When it comes to socio-economic-technical decisions four criteria should be considered as main factors of sustainability: technological, environmental, economic and social criteria (Saaty and Begicevic 2010). In the following a simple example for a hierarchic structure is given in figure 2 based on this criteria to support the decision process for technology selection.



**Figure 1:** Simple example for a hierarchic structure for technology choice based on four main criteria

**Note:** technological performance (TP), environmental impact (EI), Economic performance (EP) and Social impacts (SI)

After establishing a hierarchic structure comparisons based on a 1-9 Likert scale of absolute numbers have to be carried out to gather the relative importance of each criterion. The basic question here for is: *how many times more dominant is one element than the other with respect to a certain criterion or attribute?* This comparison expresses the preference to a certain attribute assigned by an individual or a group of participants (Perera and Sutrisna 2010). In case of participants related to a certain group or sub-regime, preference numbers can be averaged to obtain a weighted average. The comparisons provide the base for a square matrix in which  $a_{ji}$  represents the weight ratios ( $w_j/w_i$ ). The remaining matrix elements represent the reciprocal property of the matrix through  $a_{ji}=1/a_{ij}$  and  $a_{jj}=1$  (Perera and Sutrisna 2010) (Saaty 1987). Then maximum *Eigenvalues*, consistency index  $CI = (\lambda_{max} - n)/(n - 1)$  in which  $\lambda$  represents the maximum *Eigenvalue*, consistency ratio  $CR = CI/RI$  (RI is the random consistency of sample size 500 matrices) and the normalized values for each criteria have to be calculated. If this conditions are satisfied a decision or prioritization of actions can be made else the procedure has to be repeated (Saaty 1977)(Demirtas 2013). A detailed description of the mathematical procedures is given in (Saaty 1977).

In the following a random example based on the simplified Geometric Mean method (Saaty 1987) was conducted to clarify the procedure. The aim of the example is to identify and rank the relevance of main criteria prioritization for technology selection. The calculus and its results are depicted in figure 2.

Reciprocal matrix						Normalization				
	EI	EP	SI	TP		EI	EP	SI	TP	
EI	$\begin{pmatrix} 1,00 & 5,00 & 3,00 & 3,00 \\ 0,20 & 1,00 & 3,00 & 1,00 \\ 0,33 & 0,33 & 1,00 & 0,33 \\ 0,33 & 1,00 & 3,00 & 1,00 \end{pmatrix}$				=	EI	$\begin{pmatrix} 0,54 & 0,68 & 0,30 & 0,56 \\ 0,11 & 0,14 & 0,30 & 0,19 \\ 0,18 & 0,05 & 0,10 & 0,06 \\ 0,18 & 0,14 & 0,30 & 0,19 \end{pmatrix}$			
EP					EP					
SI					SI					
TP					TP					
Summ	1.82	8.56	19.26	18.00		Summ	1	1	1	1
Geometric mean/ weights					Dominance and Paretoa analysis					
	Criteria				Rank	Contribution to problem				
EI	$\begin{pmatrix} 0,50 \\ 0,17 \\ 0,08 \\ 0,19 \end{pmatrix}$	Environmental Impacts			1	0,52				
EP		Economic Performance			2	0,20				
SI		Social Impacts			3	0,18				
TP		Technology Performance			4	0,10				

**Figure 2:** Simple example for a AHP Process based on four dimensions

Based on this random example a CI of 0.09 was calculated to prove that the reciprocal matrix is consistent. This is followed by the calculation of CR (Saaty 1977). The result is  $0.093 < 0.1$  and the comparison can be considered as quite consistent. At the end the weights of different criteria can be obtained based on stakeholder preferences. This allows it to perform a prioritization ranking for potential actions that can be taken regarding optimal technology design or choice. In this randomly generated case the participating stakeholder would be mainly concerned about environmental impacts, followed by the economic performance, social impacts and finally performance of a certain technology.

## ***Integrative role of AHP within the research***

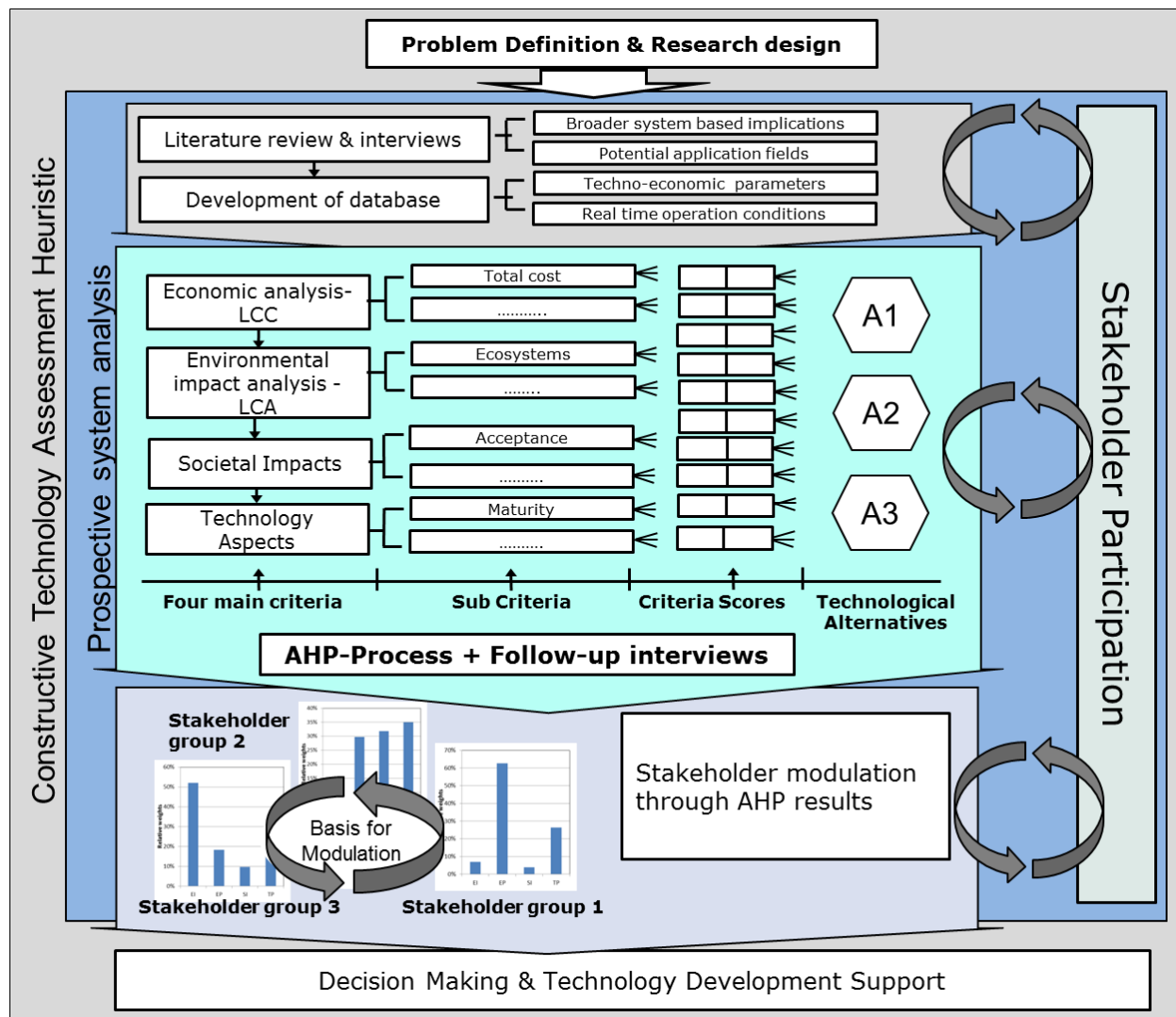
The research is conducted under the general idea of CTA to support broader interactions and to offer a space where actors can probe each other worlds.

AHP allows grasping multiple constructed realities in differences within perceptions, attitudes, judgments and practices of various actors. In this sense it provides a solid base for stakeholder modulation following the principles of CTA by allowing differences in opinions to develop a best construct of how technology should be (Perera and Sutrisna 2010). The ranking of criteria and sub-criteria represents different perspectives and interests of various stakeholders embedded in different socio-technical sub-regimes already making them transparent and debatable. The method can also provide an indicator for developers what aspects may influence the success of their technology by decomposing AHP results e.g. through Pareto Analysis to prioritize more specific “adjustment screws” (given by criteria) to match the product with the selection environment.

Further decisions and preferences are expressed in form of equations, inputs and coefficients which can be observed and reproduced by other specialists (Alcamo 2008). In this way AHP provides important, reproducible insights and allows grasping strategic intelligence about influence parameters of new technologies according to sustainability which at the end result from their socio-technical embedment.

### ***Resulting research design***

The use of mixed methods through the lens of CTA enables the creation of a broader base for specific technology development support and policy advice and allows it to make modeling assumptions and scenarios more reflexive, to check plausibility, logical causality, epistemic validation and consistency leading to amendments and transparency of the research on table. A general overview of the proposed methodology and summary for the planned research is given in figure 3.



**Figure 3:** Resulting research design for prospective system analysis following heuristics of CTA

## Conclusion and outlook

Battery systems with various existing as well as emerging chemistries and vertical system integration possibilities are the technology in the foci of this research. Regarding literature technological trajectory of grid battery storage can be considered as a blurry, unforeseeable future highly dependent on

various exogenous factors as past developments have shown. This is grounded in the high uncertainty about the general needs and requirements regarding energy storage and sustainability in combination with large socio-technical regime changes. A dilemma resulting from this uncertainty is the challenge to identify technology “shape targets” or weighting of results (environmental, economic impacts etc.) that inform technology developers. Not less challenging is the task to develop a methodology under this insufficient information being highly dependent on shared expectations of the present. This situation has led to a methodological positioning of the work towards pragmatism or the use of mixed methods in strong orientation to the principles of CTA. Within the research AHP supports multiple methods in data collection in a qualitative and quantitative way and enables the analyst to combine results from PSA with qualitative actor notions about technology according the surrounding environment where it is embodied. It allows to rank different criteria relevant for technology selection and to derive factors which lead to a best construct of technology within a certain decision environment.

In this sense the developed integrative approach offers a possibility to combine participative approaches and formal quantitative tools to explore potential sustainability implications of an optimum construct of energy storage technologies in the future and to analyze uncertainty. The PSA can provide important insights and allows the generation of in-depth knowledge about relevant techno-economic and environmental parameters and their interrelation grounded in the principles of CTA. The research design allows it to shape technology in a more sustainable way in frame of „Responsible Research and Innovation“.

First results of the ongoing PSA part can be found in (Baumann, Zimmermann and Dura, 2013, Zimmermann et al. 2013, Baumann et al. 2012). First exploratory interviews have already been conducted and will soon be published. Further works in the future will include the distribution of the AHP questionnaire to already identified experts within the energy system, academia and policy and will be flanked by selected follow-up interviews.

## References

- Alcamo, Joseph. 2008. Chapter Six The SAS Approach: Combining Qualitative and Quantitative Knowledge in Environmental Scenarios. In *Developments in Integrated Environmental Assessment*, 2:123–50. Elsevier.

<http://linkinghub.elsevier.com/retrieve/pii/S1574101X08004067>.

- Baumann, Manuel. 2013. A Constructive Technology Assessment of Stationary Energy Storage Systems - A Prospective Life Cycle Orientated Analysis. *IET Working Papers Series*. WPS01/2013
- Baumann, Manuel et al. 2012. Systemanalytische Untersuchungen für elektrochemische Speicher. Presented at the *Alternative Antriebskonzepte bei sich wandelnden Mobilitätsstilen*, Karlsruhe, March 8.
- Baumann, M., B. Zimmermann and H. Dura. 2013. A Comparative Probabilistic Economic Analysis of Selected Stationary Battery Systems for Grid Applications. Alghero, Sardinia – Italy: IEEE.
- Bell, Sarah. 2011. *Engineers, Society, and Sustainability*. San Rafael, Calif.: Morgan & Claypool. <http://dx.doi.org/10.2200/S00378ED1V01Y201108ETS017>.
- Cherryholmes, C. H. 1992. Notes on Pragmatism and Scientific Realism. *Educational Researcher* 21 (6): 13–17. doi:10.3102/0013189X021006013.
- Collingridge, David. 1980. *The Social Control of Technology*. New York: St. Martin's Press.
- Creswell, John W. 2003. *Research Design: Qualitative, Quantitative, and Mixed Method Approaches*. 2nd ed. Thousand Oaks, Calif: Sage Publications.
- Demirtas, Demirtas. 2013. Evaluating the Best Renewable Energy Technology for Sustainable Energy Planning. *International Journal of Energy Economics and Policy* Vol 3 (Special Issue): 22–33.
- Fleischer, Torsten, and Armin Grunwald. 2008. Making Nanotechnology Developments Sustainable. A Role for Technology Assessment? *Journal of Cleaner Production* 16 (8-9): 889–98. doi:10.1016/j.jclepro.2007.04.018.
- Geels, Frank. 2005. Co-Evolution of Technology and Society: The Transition in Water Supply and Personal Hygiene in the Netherlands (1850–1930) - A Case Study in Multi-Level Perspective. *Technology in Society* 27 (3): 363–97. doi:10.1016/j.techsoc.2005.04.008.
- Genoese, Fabio. 2013. Modellgestützte Bedarfs- Und Wirtschaftlichkeits Analyse von Energiespeichern Zur Integration Erneuerbarer Energien in Deutschland. Dissertation, Karlsruhe: Karlsruhe Institute of Technology. <http://d-nb.info/1034864947/34>.
- Goodwin, Paul. 2004. *Decision Analysis for Management Judgment*. 3rd ed. Hoboken, NJ: Wiley.
- Grünwald, Philipp H. et al. 2012. The Socio-Technical Transition of Distributed Electricity Storage into Future networks—System Value and Stakeholder Views. *Energy Policy* 50 (November): 449–57. doi:10.1016/j.enpol.2012.07.041.
- Grunwald, Armin. 1999. *Rationale Technikfolgenbeurteilung: Konzepte Und Methodische*



- Grundlagen*. Vol. 1. Wissenschaftsethik Und Technikfolgenbeurteilung. Berlin-Heidelberg: Springer.
- Grunwald, Armin. 2002. *Technikfolgenabschätzung- Eine Einführung*. Vol. 1. Gesellschaft - Technik - Umwelt 1. Berlin: Edition Sigma.
- Grunwald, Armin. 2012. Sustainability Assessment of Technologies - An Integrative Approach. In *Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment*, 35–62.
- Grunwald, Armin. 2011. Energy Futures: Diversity and the Need for Assessment. *Futures* 43 (8): 820–30. doi:10.1016/j.futures.2011.05.024.
- Guston, David H. and Daniel Sarewitz. 2002. Real-Time Technology Assessment. *Technology in Society* 24 (1-2): 93–109. doi:10.1016/S0160-791X(01)00047-1.
- Hämäläinen, Raimo P. and Timo O. Seppäläinen. 1986. The Analytic Network Process in Energy Policy Planning. *Socio-Economic Planning Sciences* 20 (6): 399–405. doi:10.1016/0038-0121(86)90054-6.
- Hochgerner, J. et. al. 2008. *Open Innovation*. Wien: Zentrum für Soziale Innovation. [https://zsi.at/attach/Open\\_Innovation\\_Endbericht.pdf](https://zsi.at/attach/Open_Innovation_Endbericht.pdf).
- Kemp, René. 1994. Technology and the Transition to Environmental Sustainability. *Futures* 26 (10): 1023–46. doi:10.1016/0016-3287(94)90071-X.
- Kuhlmann, Stefan. 2013. Strategische Und Konstruktive Technikfolgenabschätzung. In *Konzepte Und Verfahren Der Technikfolgenabschätzung*, edited by Georg Simonis, 129–43. Wiesbaden: Springer Fachmedien Wiesbaden. [http://link.springer.com/10.1007/978-3-658-02035-4\\_8](http://link.springer.com/10.1007/978-3-658-02035-4_8).
- Leonhard, W. et al. 2008. *VDE-Study: Energy Storage in Power Supply Systems with a High Share of Renewable Energy Sources*. Frankfurt am Main: VDE.
- Murphy, John P. and Richard Rorty. 1990. *Pragmatism: From Peirce to Davidson*. Boulder: Westview Press.
- Patton, Michael Quinn. 2002. *Qualitative Research and Evaluation Methods*. 3 ed. Thousand Oaks, Calif: Sage Publications.
- Perera, N. and M. Sutrisna. 2010. The Use of Analytic Hierarchy Process (AHP) in the Analysis of Delay Claims in Construction Projects in the UAE. *The Built & Human Environment Review* Volume 3 (Special Issue 1): 29–48.
- Ravetz, Joe. 1999. Factor Four: Doubling Wealth-Halving Resource Use, *Business Strategy and the Environment* 8 (2): 146–47.
- Rip, Arie and Haico te Kulve. 2008. Socio-Technical Scenarios To Support Constructive Technology Assessment Of Nanotechnology. in *The Yearbook of Nanotechnology in Society, Volume I: Presenting Futures*.

- Robinson, Douglas. 2010. *Constructive Technology Assessment of Emerging Nanotechnologies Experiments in Interactions*. Enschede: University of Twente. [http://doc.utwente.nl/74640/1/thesis\\_D\\_Robinson.pdf](http://doc.utwente.nl/74640/1/thesis_D_Robinson.pdf).
- Roes, A.L. and M.K. Patel. 2011. Ex-Ante Environmental Assessments of Novel Technologies – Improved Caprolactam Catalysis and Hydrogen Storage." *Journal of Cleaner Production* 19 (14): 1659–67. doi:10.1016/j.jclepro.2011.05.010.
- Saaty, R.W. 1987. The Analytic Hierarchy Process—what It Is and How It Is Used. *Mathematical Modelling* 9 (3-5): 161–76. doi:10.1016/0270-0255(87)90473-8.
- Saaty, Thomas L. 1977. A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology* 15 (3): 234–81. doi:10.1016/0022-2496(77)90033-5.
- Saaty, Thomas L. 1990. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. Pittsburgh, PA: RWS Publications.
- Saaty, Thomas L. and Nina Begicevic. 2010. The Scope of Human Values and Human Activities in Decision Making. *Applied Soft Computing* 10 (4): 963–74. doi:10.1016/j.asoc.2010.04.002.
- Schot, Johan and Arie Rip. 1997. The Past and Future of Constructive Technology Assessment. *Technological Forecasting and Social Change* 54 (2–3): 251–68. doi:10.1016/S0040-1625(96)00180-1.
- Schreuer, Anna; Michael Ornetzeder and Harald Rohrer. unknown. *Participatory Technology Development and Assessment: In Search of a Sustainable Use of Fuel Cell Technology at the Municipal Level*. Austria.
- Van Merkerk, Rutger O. and Ruud Smits. 2008. Tailoring CTA for Emerging Technologies. *Technological Forecasting and Social Change* 75 (3): 312–33. doi:10.1016/j.techfore.2007.01.003.
- Van Merkerk, Rutger O. and Harro van Lente. 2005. Tracing Emerging Irreversibilities in Emerging Technologies: The Case of Nanotubes. *Technological Forecasting and Social Change* 72 (9): 1094–1111. doi:10.1016/j.techfore.2004.10.003.
- Verbong, G.P.J. and F.W. Geels. 2010. Exploring Sustainability Transitions in the Electricity Sector with Socio-Technical Pathways. *Technological Forecasting and Social Change* 77 (8): 1214–21. doi:10.1016/j.techfore.2010.04.008.
- Weil, Marcel. 2012. System Analysis in the Early Phase of Technology Development - Responsible Development and Production of Carbon Nanotube Paper, in Decker, M.; Grunwald, A.; Knapp, M. (eds) *Der Systemblick Auf Innovation – Technikfolgenabschätzung in Der Technikgestaltung*. Edition Sigma. Berlin
- Wietschel, M. et al. n.d. *Energietechnologien 2050 - Schwerpunkte Für Forschung Und Entwicklung: Technologiebericht*. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI.

Zimmermann, B., et al. 2013. A Comparative Analysis of the Cumulative Energy Demand of Stationary Grid-Integrated Battery Systems. In , 248–53. Alghero, Italy: IEEE. doi:10.1109/ICCEP.2013.6586997.